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TAKING ADVANTAGE OF THE HYBRID EFFECT IN THIN-PLY PSEUDO-DUCTILE LAMINATES

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Abstract
Hybrid laminates and angle-ply laminates with thin unidirectional carbon plies have been shown to give a pseudo-ductile response with more gradual failure. This paper shows the effect of ply thickness on the initial tensile failure strain. Significant enhancements to the failure strain are demonstrated in glass-carbon hybrid composites, in hybrids with different grades of carbon fibre and in carbon fibre laminates combining 0˚ and angle plies. In addition to providing pseudo-ductility, these laminates therefore enable greater advantage to be taken of the intrinsic properties of the materials.

1. Introduction

Composite materials have excellent specific strength and stiffness, but a major drawback is their lack of ductility. The High Performance Ductile Composites Technology (HiPerDuCT) programme is a collaboration between the University of Bristol and Imperial College to address this challenge by developing new materials and architectures that give a more gradual failure.

It has been shown that using thin-ply hybrid laminates, delamination can be suppressed, and progressive fragmentation of the high modulus plies can be obtained [1]. This gives a pseudo-ductile unidirectional tensile response with a plateau in the stress-strain curve, e.g. Fig. 1.

A second mechanism is fibre reorientation in angle ply laminates, which can produce significant additional strain as the fibres become more aligned with the loading direction [2]. This has been shown to be recoverable, with no loss of initial modulus on reloading, and therefore represents ductile rather than pseudo-ductile strain [3].

These mechanisms can be combined in angle ply laminates containing thin 0˚ plies which fragment followed by reorientation of the angle plies [4], producing a longer plateau. These laminates are pseudo-ductile, because the fragmentation leads to loss of modulus even though the fibre reorientation does not [3].

Tests on glass-carbon laminates have confirmed that there is a hybrid effect when the carbon plies are very thin, leading to a significant increase in the strain at failure [5]. The mechanism responsible for the hybrid effect is the constraint of the adjacent plies limiting the development of critical clusters of fibre breaks, and so may also apply in laminates of the same material where fibre fracture is not catastrophic.

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This paper investigates various configurations of laminates, showing the magnitude of the enhancement of the failure strain that can be obtained. The results demonstrate that as well as the pseudo-ductile response these laminates enable greater advantage to be taken of the properties of the basic materials by exploiting the hybrid effect.

2. Hybrid effect in glass-carbon laminates

Various combinations of glass/carbon hybrids were tested in tension [5]. The materials were S2-glass/913 epoxy prepreg supplied by Hexcel with a standard thickness of 0.155mm, and TR30 carbon/K50 epoxy prepreg only 0.029mm thick from SK Chemicals (designation USN020). The resins were both 120°C cure systems, which were found to be compatible.

Laminates with the layups given in Table 1 were cured and specimens 20 mm wide with a 160 mm gauge section were cut, and end-tabbed. Tests were carried out under uniaxial tensile loading at a crosshead speed of 2 mm/min. Strains were measured using a videogauge with a nominal gauge length of 130 mm. A minimum of five specimens were tested from each configuration.

Table 1. S-glass / Carbon hybrid specimen types.

Specimen Type	Fibre areal mass	Nominal thickness	Relative carbon layer thickness	Modulus	Knee point strain corrected for residual stress (CV)
	[g/m^2]	[mm]		[GPa]	[%] [rel. %]
SG/TR30/SG	190/21/190	0.339	0.085	¿	2.227 (1.4)
SG/TR30$_2$/SG	190/42/190	0.368	0.157	¿	2.004 (1.6)
SG/TR30$_3$/SG	190/63/190	0.397	0.218	¿	1.877 (1.5)
SG$_2$/TR30$_4$/SG$_2$	380/84/380	0.736	0.157	¿	1.839 (2.1)

Specimens with 3 or 4 layers of carbon failed with a single fracture in the carbon in the gauge section, followed by complete delamination of the carbon from the glass. This was accompanied by a sharp load drop, and the strain at this point was recorded. Specimens with 1 or 2 layers failed by progressive fragmentation of the carbon plies with no load drop. There was a plateau on the stress-strain curve, and the failure strain was estimated from the intersection of straight lines fitted to the plateau and the initial loading response, as shown in Fig. 2. Strains were also corrected for the small effect of thermal residual stresses due to the different expansion coefficients of the glass and carbon.

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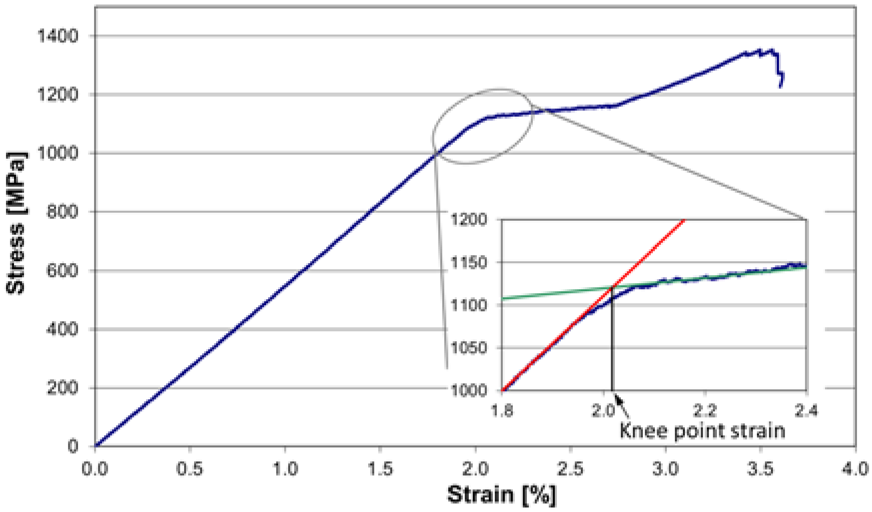

Figure 1. Typical pseudo-ductile response of (SG/TR302/SG) glass/carbon hybrid,and method for defining failure strain

Results are shown in Fig. 2. Failure strains for the 3 and 4 ply cases were similar, both close to the fibre failure strain of 1.9% quoted on the manufacturer's datasheet. Failure strains for the laminates with thinner carbon layers are higher, with values of 2.00% and 2.23% for the double and single ply cases compared with an average of 1.86% for the thicker plies, relative increases of about 8% and 20%.

It can also be seen that there is a slight slope on the plateau as progressively stronger parts of the carbon ply fail. The maximum strain in the carbon ply at the end of the plateau when fragmentation is saturated is estimated to be 2.35% [5].

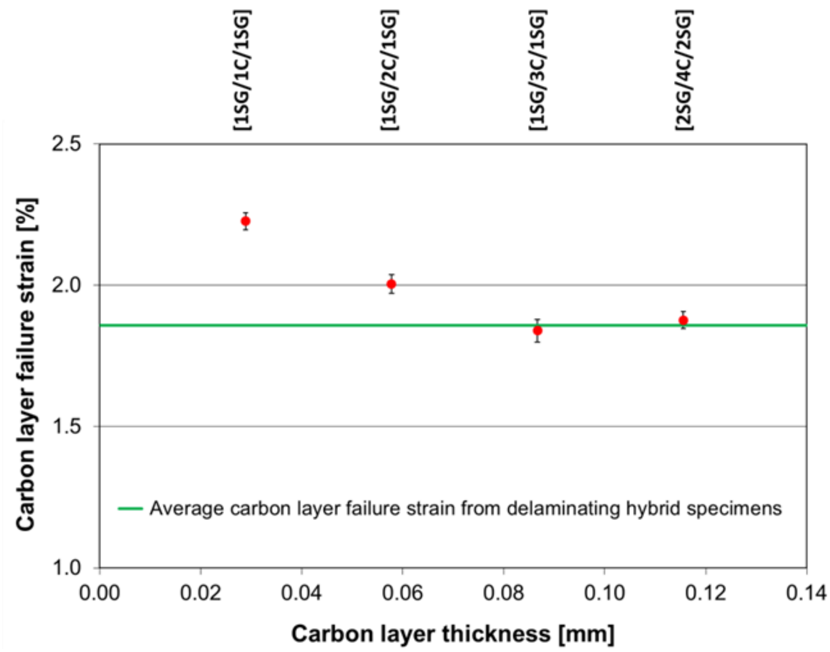

Figure 2. Hybrid effect for thin carbon layers [5]

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3. Hybrid effect in carbon-carbon laminates

A hybrid effect was also observed in tests on similar specimens made from laminates of ultra high modulus carbon/epoxy. Materials were North Thin Ply Technology ThinPreg 120 EPHTg-402 with T1000 intermediate modulus and XN80 ultra high modulus carbon fibres, with ply thicknesses 0.032 mm and 0.050 mm respectively, and layups shown in Table 2. The ratio of layer thicknesses is much higher than the ratio of ply weights due to the higher density of the XN80 fibres. Specimen dimensions, manufacturing and test procedures were the same as for the glass/carbon hybrids.

A typical stress-strain curve is shown in Fig. 3. Failure strains were estimated using the same method as before based on the intersection of straight lines fitted to the plateau and initial response, and corrected for the small compressive strain of 0.006% due to residual thermal stresses. Five?? specimens of each type were tested. These results are also shown in Table 2.

The single ply gave a strain of 0.43% compared with 0.39% for the double ply, a relative increase of 10%. It is interesting to note that the single XN80 ply is about the same thickness as two TR30 plies, and the 10% increase in strain is similar to the 8% obtained for the double TR30 ply case. The strains in the XN80 at the end of the plateau for the single ply case are estimated to be 0.50%, a further relative 16% higher.Seems very high!

Table 2. Carbon hybrid specimen types and failure strains

Specimen Type	Aerial weights	Nominal thickness	Relative high/low strain material layer thickness	Modulus	Knee point strain corrected for residual stress (CV)
	[g/m^2]	[mm]		[GPa]	[%] [rel. %]
[$T1000_1/XN80_1/T1000_1]_S$	$[28/50/28]_S$	0.108x2	0.74	¿	0.431 (1.8)
[$T1000_2/XN80_2/T1000_2$]	56/100/56	0.217	0.74	¿	0.392 (6.1)

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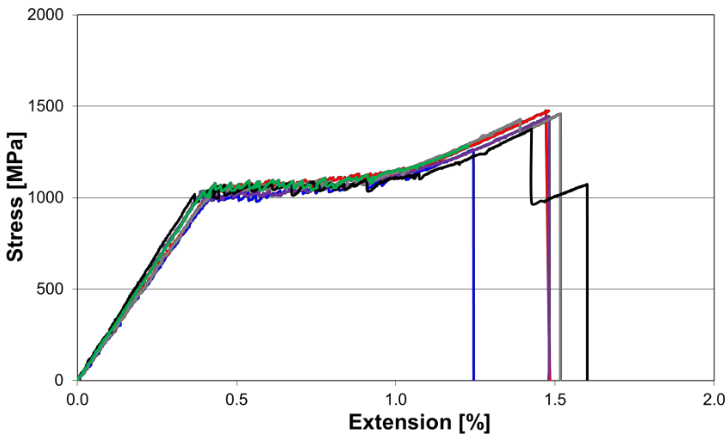

Figure 3. Stress-strain response for [$T1000_2/XN80_2/T1000_2$] carbon hybrid

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4. Hybrid effect in carbon angle-ply laminates

Two sets of carbon angle-ply laminates with different 0° ply thicknesses were tested. The first was from the same Skyflex carbon/epoxy prepreg used in the previous carbon/glass hybrid specimens, with layups containing 0° and (26/-26)° plies, as shown in Table 3.

Table 3. USN020 Carbon/epoxy angle-ply laminates and failure strains.

Specimen Type	Nominal thickness	Relative 0° layer thickness	Modulus	0° failure strain corrected for residual stress (CV)
	[mm]		[GPa]	[%] [rel. %]
$[(26/-26)_3/0/(-26/26)_3]$	0.377?	0.077	44.0	2.024 (2.7)
$[(26/-26)_5/0_2/(-26/26)_5]$	0.638?	0.091	41.1	1.895 (1.9?)

The second used North TPT YSH-70 0° plies between angle plies of either the same SK USN020 carbon epoxy used previously, or UIN020, a similar prepreg but with intermediate modulus fibres and higher volume fraction, giving a unidirectional composite modulus of 146 GPa compared with the 102 GPa of the USN020. Layer thicknesses were ???. Different combinations of angle plies were used as shown in Table 4.

Table 4. YSH-70 Carbon/epoxy angle-ply laminates and failure strains.

Layup	Materials	Nominal thickness	Relative 0° layer thickness	Modulus	0° failure strain corrected for residual stress (CV)
		[mm]		[GPa]	[%] [rel. %]
$[(22.5/-22.5)/0/(-22.5/22.5)]$	USN/YSH/USN	?	¿?	108.0	0.551 (5.3)
$[(26/-26)_3/0/(-26/26)_3]$	USN/YSH/USN	?	¿?	98.8	0.510 (3.0)
Average					0.530 (¿.?)
$[(25/-25)_2/0_2/(-25/25)_2]$	UIN/YSH/UIN	¿	¿?	134.5	0.480 (1.5)

Specimens 15 mm wide with a gauge length of 150 mm were tabbed and tested in tension under displacement control at a loading rate of 2 mm/min. The knee point strains were calculated from the intersection of lines along the plateau and the slope before fragmentation, consistent with the approach used for the hybrid specimens. However the double 0° ply USN020 specimens behaved slightly differently, showing a small load drop before the start of the plateau, as shown in Fig. 4. For this case the strain at the peak load was taken, since in the absence of a gradual start to the plateau this was a more accurate estimate of the start of fragmentation. Averages are based on a minimum of 6 specimens except for the double 0° ply USN020 case, where only 4 specimens showed a load drop, but with very consistent strains (CV only 2%).

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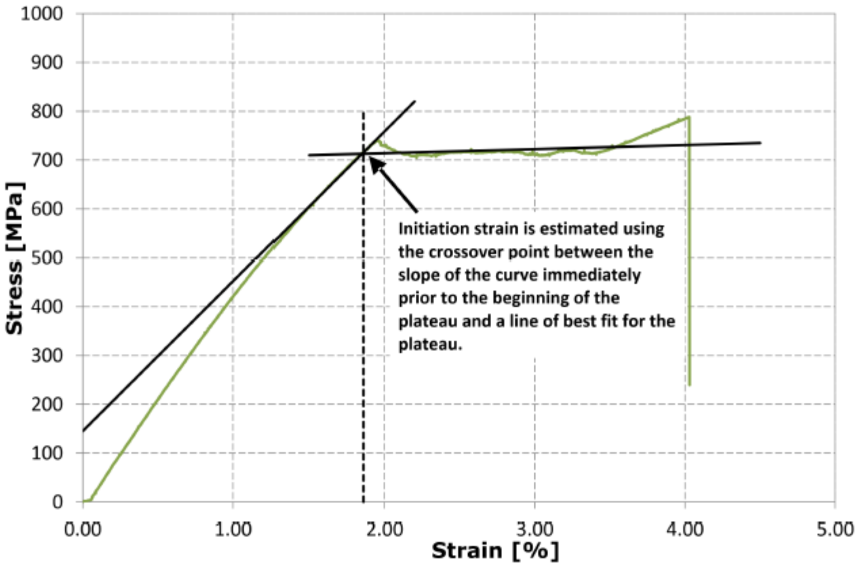

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Figure 4. Typical stress-strain response for $[(26/\text{-}26)_4/0]_s$ USN020 carbon laminate

Results are also shown in Tables 3 and 4, including the corrections for thermal residual stresses. The USN020 specimens with a single 0° ply showed a 7% relative increase in failure strain from 1.895% to 2.024%. The values and increase are similar to those from the two-ply compared with the thicker carbon/glass hybrids, but for some reason less than the values obtained with the single ply hybrid specimens. The single ply YSH specimens showed a 10% higher strain with an average for the two cases of 0.53% compared with 0.48% for the double ply case.

5. Conclusions

Significant enhancements in strain at failure were measured for laminates with thin carbon plies compared with similar specimens with thicker ply blocks, demonstrating the importance of ply thickness on tensile failure. Carbon/glass hybrids showed increases of 8% and 20% for specimens with double and single carbon plies compared to thicker specimens. A similar hybrid effect was found in carbon/carbon hybrids, with a 10% relative increase in strain at failure for single XN80 plies compared with double plies. Similar enhancements in strain at failure were observed in the 0° plies of carbon fibre laminates with angle plies, with relative increases in strain at failure of 10% and 7% for single compared with double plies of YSH-70 and TR30 fibres respectively. The first two sets of results can be interpreted as a hybrid effect. However the latter increase was obtained with a single material, demonstrating that the key factor is the ply thickness and associated constraint on the formation of a critical cluster of fibre breaks. Even higher strains are obtained further along the plateau as progressively strong parts of the carbon plies fracture. The results show that in addition to providing pseudo-ductility, these laminates enable greater advantage to be taken of the intrinsic properties of the carbon fibre materials.

Acknowledgements

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References

[1] G. Czél, M. Jalalvand, M.R. Wisnom. Design and characterisation of advanced pseudo-ductile unidirectional thin-ply carbon/epoxy–glass/epoxy hybrid composites. *Composite Structures*, 143:362–370, 2016.

[2] J.D. Fuller, M.R. Wisnom, Pseudo-ductility and damage suppression in thin ply CFRP angle-ply laminates. *Composites Part A*, 69:64–71, 2015.

[3] J.D. Fuller, M.R. Wisnom, Ductility and pseudo-ductility of thin ply angle-ply CFRP laminates under quasi-static cyclic loading. Submitted where?.

[4] J.D. Fuller, M. Jalalvand, M.R. Wisnom. Combining fibre rotation and fragmentation to achieve pseudo-ductile CFRP laminates. *Composite Structures*, 142:155–166, 2016.

[5] M. R. Wisnom, G. Czél, Y. Swolfs, M. Jalalvand, L. Gorbatikh, I Verpoest. Hybrid effects in thin ply carbon/glass unidirectional laminates: accurate experimental determination and prediction. *Composites Part A*. Submitted.

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